

Finite-size effect in shot noise in hopping conduction

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We study a current shot noise in a macroscopic insulator based on a two-dimensional electron system in GaAs in a variable range hopping (VRH) regime. At low temperature and in a sufficiently depleted sample a full Poissonian shot noise value is measured. This suggests an observation of a finite-size effect in shot noise in the VRH conduction and demonstrates a possibility of accurate quasiparticle charge measurements in the insulating regime.

As first shown by Schottky for the case of a vacuum tube, electric current can be viewed as a sequence of uncorrelated pulses corresponding to arrivals of individual electrons at the anode [1]. A mean-squared current fluctuation (shot noise) in this random Poissonian process has a spectral density of $S_I = 2qI$, where $q \equiv e$ is the elementary charge and I is the average current. A direct shot noise measurement of the charge q of a quasiparticle is intriguing in application to various solid state materials, where q can be renormalized by interactions ($q \neq e$) [2, 3]. This list includes nontrivial insulating states in charge-density wave compounds [4], in cooper pair insulators [5, 6] and in the bulk of a two-dimensional (2D) system in fractional quantum Hall effect [7].

The above concept of the charge measurement in solid state can be complicated by a non-Poissonian statistics of the current flow [8], as characterized by a Fano factor $F \leq 1$ in the expression for the noise spectral density $S_I = 2FqI$. At low enough temperatures (T) the transport in the band of localized states occurs via a variable range hopping (VRH) conduction [9]. Unlike the case of coherent transport at $T = 0$ [10], the Fano factor in the VRH regime is not universal, which is a fundamental problem for the charge measurements. Numerical calculations predict that F is determined by the ratio of the sample length L and a correlation length L_C of the critical cluster [11, 12]. The latter represents a typical distance between the most resistive (hard) hops on a random hopping network [9]. Consistently, the experiments in 2D VRH insulators [13–15] find that the Fano factor decays with the sample length roughly as $F \approx (L/L_C)^{-1}$ ($L \gg L_C$). The shot noise in the opposite limit $L \leq L_C$ is not understood. On one hand, the numerical results [12] suggest that in small samples the Fano factor remains sub-Poissonian ($F \approx 0.7$). On the other hand, the experiments do not exclude the full Poissonian noise value in sub-micrometer sized samples [13, 15].

Here we investigate the shot noise in an insulating state of a macroscopic 2D electron system of a GaAs/AlGaAs heterostructure. The Poissonian shot noise value is achieved in the VRH conduction regime at low T and in a sufficiently depleted sample. We interpret this as a manifestation of a finite-size effect in shot noise at $L \sim L_C$ and support by transport measurements. Available theories [11, 12, 16] have difficulties to explain these obser-

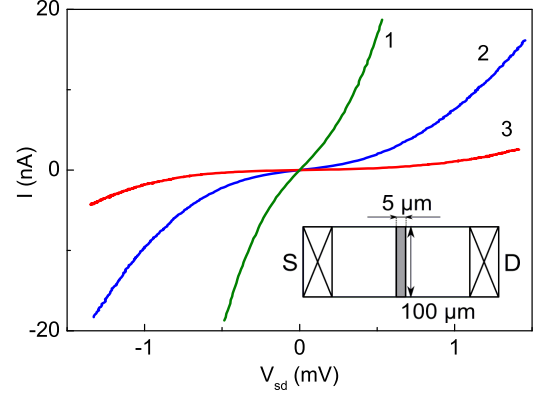


FIG. 1. I - V measurements. I - V curves at $T = 0.56$ K for a set of gate voltages in sample 1: $V_g = -0.302$ V (1), $V_g = -0.308$ V (2), $V_g = -0.339$ V (3). Inset: the sketch of the sample layout used.

vations and an alternative explanation in classical terms is proposed. Our results demonstrate a possibility of accurate measurements of the quasiparticle charge in the insulating regime.

Our samples are based on a two-dimensional electron system (2DES) in GaAs/AlGaAs buried 34 nm below the surface. The as-grown electron density and mobility (at 4.2 K) of the 2DES are, respectively, $3.5 \times 10^{11} \text{ cm}^{-2}$ and $2.8 \times 10^5 \text{ cm}^2/\text{Vs}$. A metallic front gate is used to define an insulating strip in the 2D channel with the length of $L = 5 \mu\text{m}$ along the current flow and the width of $100 \mu\text{m}$ (see the inset in Fig.1). The details of the transport and shot noise measurements are described in the supplemental material. We measured two nominally identical samples and obtained basically the same results reproducible in respect to a thermal recycling.

In fig. 1 we plot I - V curves measured at $T = 0.56$ K for a set of gate voltages V_g . A minor asymmetry of the I - V curves in respect to the origin is related to a grounding of the drain contact. As a result the effective gate voltage is more positive at negative currents, so that the negative I - V branches are more conducting. All the I - V s are strongly nonlinear and the nonlinearities become more pronounced with the sample depletion. The nonlinearities also strengthen when the T is decreased,

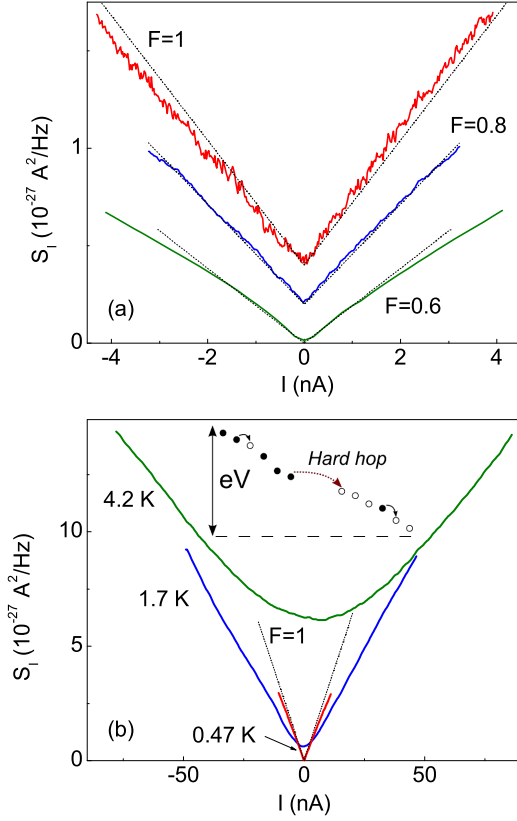


FIG. 2. Shot noise measurements. (a) – Shot noise spectral density as a function of current at $T = 0.56$ K (sample 1). The resistivity (the Mott temperature) from top to bottom are: $R_{\square} = 58$ M Ω ($T_0 \approx 300$ K), $R_{\square} = 8.8$ M Ω ($T_0 \approx 140$ K), $R_{\square} = 1$ M Ω ($T_0 \approx 40$ K). The dashed lines are fits used to extract the Fano factor. The scales on both axes are reduced by a factor of 50 (5) for the lowest (middle) curve and the two upper curves are vertically offset in steps of 2×10^{-28} A 2 /Hz. (b) – Shot noise spectral density as a function of current for three temperature values and $R_{\square} = 26$ M Ω (at $T = 0.47$ K), $T_0 \approx 300$ K (sample 2). The dashed guide line corresponds to $F = 1$. Inset – a sketch of hopping along a quasi-1D filament of the VRH network with a hard-hop in the middle. The empty/occupied localized states are depicted as, respectively, the empty/filled circles.

see supplemental material.

Next we turn to the shot noise measurements in this strongly nonlinear regime. Fig. 2a shows the noise spectral density as a function of current at $T = 0.56$ K for a set of gate voltages. The dependencies $S_I(I)$ are almost symmetric in respect to the current reversal and linear at not too high $|I|$, which is characteristic for the shot noise. The Fano factor determined from this linear region is seen to increase with the sample depletion. Note that in order to tune F between 0.6 and 1 one has to vary the linear response resistance by about two orders of magnitude. Fig. 2b demonstrates the T -dependence of the shot noise at fixed V_g . At higher T the Fano factor is determined outside a crossover region between the

equilibrium Johnson-Nyquist noise and the shot noise. Here F increases from ≈ 0.4 to ≈ 0.9 when the sample is cooled down from 4.2 K to 0.47 K. The central result of our paper, shown in fig. 2, is that at low enough T and for a strong enough depletion the shot noise in a macroscopic sample can reach the maximum possible Poissonian value $F = 1.0 \pm 0.1$ [17]. This behavior can be interpreted as an observation of a finite-size effect in shot noise. Below we demonstrate that our samples are macroscopic VRH insulators. That is to say, that the observation of $F \approx 1$ basically represents an accurate measurement of the quasiparticle charge in the VRH conduction regime.

Gate voltage dependencies of the linear response resistivity R_{\square} are plotted in fig. 3a for two temperatures 4.2 K and 0.5 K. The resistivity is found to strongly increase at sample depletion without significant mesoscopic fluctuations. This data demonstrates a roughly exponential dependence of R_{\square} on the carrier density and indicates a strong localization of the electrons. In fig. 3b we plot the conductivity $G_{\square} \equiv 1/R_{\square}$ as a function of T for different values of V_g . With decreasing T the conductivity drops by 1-2 orders of magnitude. Above 0.2 K the T -dependencies are best described by the Mott VRH law in 2D: $\ln G_{\square} \propto -(T_0/T)^{1/3}$ (dotted lines). Here $T_0 = 13.8/(k_B g a^2)$ is the Mott temperature, g – the density of states at the Fermi level and a – the localization radius [9]. As seen from fig. 3b, T_0 increases with the sample depletion, which we associate with the decrease of a and g . Note that a thermal recycling typically caused some shift of the gate voltage position of the mobility edge. For this reason, the data from different cryostats were taken at different V_g , so that the T -dependencies coincide in the range where they overlap. Such data are shown by different symbols in fig. 3b. At low T we observe deviations from the Mott VRH law and the T -dependencies slow down. We have checked via noise measurements that the electronic T follows that of the bath down to 100 mK, i.e. the deviation is unlikely to be caused by an electromagnetic pick-up.

As demonstrated in figs. 2 and 3, our samples exhibit the Poissonian shot noise value and behave like macroscopic VRH insulators. Below we argue that this effect in our samples is a result of a finite-size effect in the VRH conduction [18, 19]. The key properties of the VRH conduction are captured by a model of the Miller-Abrahams random resistor network (see, e.g., [9]). The model assumes that a pair of localized states, separated by a distance r_{ij} , is connected by a resistor $R_{ij} = R_0 \exp \xi_{ij}$, where $\xi_{ij} = 2r_{ij}/a + \varepsilon_{ij}/k_B T$ and ε_{ij} is determined by the energies of the two states and the chemical potential. The percolation theory calculates a resistivity of this network by connecting only those resistors with $\xi_{ij} \leq \xi_C$, where $\xi_C = (T_0/T)^{1/3}$ is a percolation threshold [9]. This applies for localized states separated by an average distance (hop length) $l_T = a \xi_C$. The resistivity is determined by the hard hops with the resistances $R_0 \exp \xi_C$ and the correlation length $L_C = l_T (T_0/T)^{\nu/3} = a (T_0/T)^{(\nu+1)/3}$, where $\nu = 4/3$ is the 2D critical index.

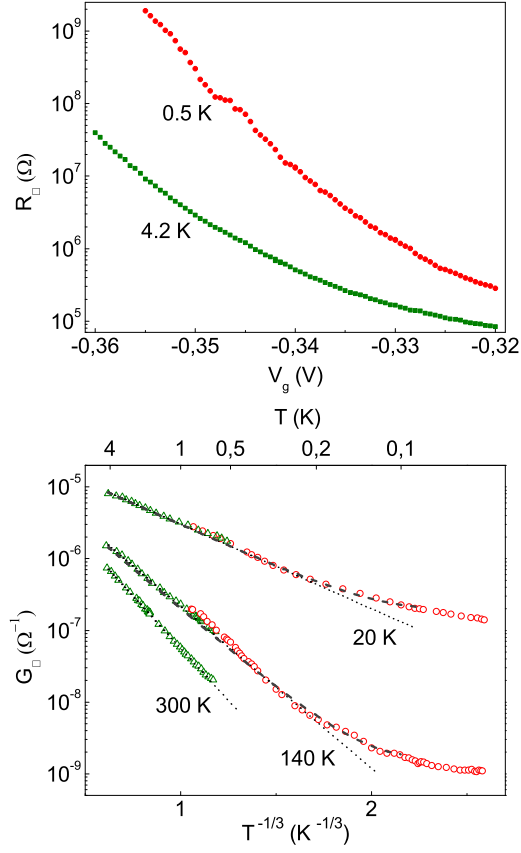


FIG. 3. Linear response resistance/conductance. (a) – Gate voltage dependencies of the resistivity at two different temperatures (sample 1). (b) – T dependence of the conductivity in sample 1 for three different depletions (see text). The best fits to the Mott VRH law are plotted as the dotted lines and the respective values of T_0 are shown nearby. The fits to the low- T deviations from the Mott law on the two upper curves are shown by the dashed lines. The fit parameter T_P equals 0.14 K/0.2 K for the top/middle curves (see text).

In our samples L_C is varied by changing the T or the gate voltage. The experimental uncertainty in a allows to roughly estimate the maximum correlation length [20] as $1.3 \mu\text{m} \leq L_C \leq 4 \mu\text{m}$ at $T \approx 0.5$ K. At small depletions and/or high T the L_C is considerably smaller than the sample length $L = 5 \mu\text{m}$, whereas in the opposite limit they are comparable. As seen from fig. 2, in the latter case $F \approx 1$. We also find that the dependence of F on the ratio L/L_C is considerably weaker compared to the asymptotic law $F \propto (L_C/L)^{0.8}$ at $L \gg L_C$ [11, 14]. In fig. 2b the observed change in F is roughly twice smaller than follows from this prediction and is qualitatively consistent with the saturation of F at $L \sim L_C$ in numerical calculations [12]. Hence the onset of the Poissonian shot noise in our samples is a result of the finite-size effect $L \sim L_C$ in the VRH regime.

Transport measurements give further evidence for the finite-size effect in the VRH regime. In a finite sam-

ple, the percolation threshold falls below that for an infinite system [18]. This gives rise to a low T deviation of the dependencies $G_{\square}(T)$ from the Mott law, as indeed observed in fig. 3b. For small deviations one has [18] $\ln G \propto -(T_0/T)^{1/3} + 0.25(T_P/T)^{7/3}$, where T_P is a crossover temperature at which $L \sim L_C$. The data of fig. 3b is in reasonable agreement with this formula with T_P as a fit parameter (dashed lines). The T dependence of the $I-V$ nonlinearity is also consistent with the finite-size effect, see supplemental material.

In the regime $L \sim L_C$, the Miller-Abrahams network breaks up into quasi-1D filaments [18] connecting the source and drain reservoirs in parallel. The observation of the Poissonian shot noise is quite surprising even in this regime, because of a large number of hops involved. For instance the upper curve in fig. 2a corresponds to $l_T \sim 250$ nm, giving at least $L/l_T \sim 20$ hops per filament. Since their contributions to the total current and noise are additive, in the following we consider the noise of just one such filament. In a circuit model [16], the i -th hop in a path is treated as an independent Poissonian noise source with a resistance $R_i = R_0 \exp \xi_i$. In the VRH regime R_i belong to a geometrical sequence with a common ratio of ~ 3 [9], which results in $F = \sum R_i^2 / (\sum R_i)^2 \approx 0.5$. In order to obtain $F = 0.9$, which is the lowest bound to the experimental value, an unreasonably broad distribution of R_i has to be assumed (a common ratio of 20). This scenario is unlikely, especially in the regime $L \sim L_C$, where the resistance network is more uniform than in an infinite sample [18].

We suggest an alternative approach to the shot noise in the VRH conduction based on a purely classical model. Ref. [21] consider a so-called open boundary asymmetric exclusion process, which describes a hopping of particles on a uniform 1D lattice. The hopping is allowed only in one direction, unless the corresponding site is occupied. In the two limiting cases of low and high densities, the Fano factor approaches unity as $F = 1 - 2\rho$, where $\rho \ll 1$ is, respectively, the average occupancy of particles or holes (empty sites). As pointed out by [16], this is a result of independent hopping of the particles (holes) across the lattice at $\rho \rightarrow 0$, analogous to the original Schottky's problem. This gives a hint how to understand the Poissonian noise in the VRH regime with $L \sim L_C$. Consider a hopping chain of $2N$ localized states (sites). The hopping rates between the i -th and $i+1$ -th sites have an exponentially broad distribution ($\Gamma_i \propto \exp(-\xi_i)$) belong to the geometrical sequence with a common ratio of ~ 3). In the strongly nonlinear regime $|eV| \gg k_B T$ the electrons hop preferentially in the direction of the lower chemical potential (from the left to the right, see the inset of fig. 2b). The hard-hop with the smallest rate Γ_H is assumed to be in the middle. Most of the time, we expect that the states on the left hand side of the hard hop are occupied, whereas those on the right hand side are empty. The total number of electrons on the sites $i > N$ is equal to a product of the injection rate Γ_H and

the average dwell time $T_{\text{dwell}} = \sum_{i>N} (\Gamma_i)^{-1}$. Hence, the average occupancy on the right hand side from the hard-hop is $\rho = \Gamma_H T_{\text{dwell}} / N \sim (2N)^{-1} \ll 1$. A similar relation holds for the holes on the left hand side from the hard-hop. Following Ref. [21] one finds $F = 1 - 2\rho \approx 0.9$ not so far from the experiment ($N = 10$). This indicates that the classical approach is a promising framework to understand the shot noise in the VRH conduction regime.

In summary, we investigated the shot noise in a macroscopic VRH insulator based on a 2D electron system in GaAs. At low T and strong enough depletion the full

Poissonian noise is observed, which is interpreted as a manifestation of the finite-size effect. We propose a classical approach capable to explain this result and apparently consistent with the VRH conduction theory. Our results open up a possibility for accurate quasiparticle charge measurements in nontrivial insulating states.

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SUPPLEMENTAL MATERIAL

Finite-size effect in shot noise in hopping conduction

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I. EXPERIMENTAL DETAILS

A two-terminal resistance and I - V curves were measured with a low-noise 100 M Ω input resistance preamplifier and a $\sim 300 \Omega$ series resistance was subtracted. For noise measurements the sample was connected in series with a load resistor $R_0 = 1 \text{ k}\Omega$. A voltage noise on R_0 was amplified by a set of rf-amplifiers and detected in the frequency band 10-20 MHz. A total gain of the circuit was about 70 dB. The first cascade of amplification was represented by a home-made low- T amplifier placed nearby (about 1 cm) the sample. Analyzing the data we treated the load resistor, the ohmic contacts and the 2D channel as independent noise sources. The respective rf-impedances are equal to the dc differential resistances [1], obtained by a numerical differentiation of the I - V curves. The absolute calibration was utilized via the Johnson-Nyquist noise measurements, with both the T and the sample resistance varied. In this approach the influence of a shunt capacitance (on the order of 5 pF) is automatically absorbed into the (load-dependent) gain. An example of one such measurement is shown in fig. 1. Note that we measured the shot noise at frequencies at least two orders of magnitude higher than in previous experiments [2–4]. This allowed to completely get rid of the $1/f$ and other spurious noises, such that S_I is frequency independent in the range 10-100 MHz. The noise measurements were performed in a liquid ^3He cryostat in the range $0.5 \text{ K} \leq T \leq 4.2 \text{ K}$. A $^3\text{He}/^4\text{He}$ dilution refrigerator was used to extend the T -range of the resistance measurements down to 60 mK.

II. T -DEPENDENCE OF THE NONLINEARITY

The nonlinearities of the $I - V$ curves are more pronounced at lower T , that can be characterized by a T dependence of the threshold bias voltage V_{th} . In the absence of a clear threshold behavior we define V_{th} as the bias voltage corresponding to a 20% deviation of the I - V from the linear dependence at small V . The V_{th} increases approximately linearly with T , as shown in fig. 2. This observation is insensitive to the criterium used to define V_{th} . The dependence $V_{th}(T)$ is qualitatively consistent with the finite-size effect. According to [5], for $L \sim L_C$ the electrochemical potential drops across a single hard hop, which results in a linear T dependence $V_{th} \propto T$. This is indeed the case in our samples in the parameter

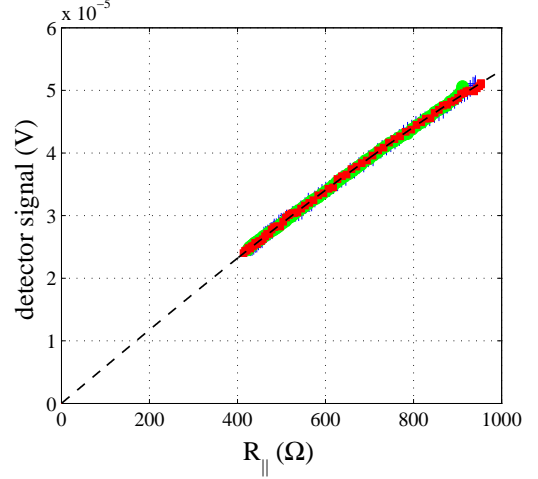


FIG. 1. Measurement of the equilibrium Johnson-Nyquist voltage noise in the dilution refrigerator. The excess voltage on the detector (normalized by T) as a function of the resistance of the sample and load R_0 in parallel. Different symbols correspond to the different bath temperatures: circle – 1.23 K, plus – 0.69 K, square – 0.125 K. The dashed line is the fit corresponding to the Johnson-Nyquist noise shunted by a stray capacitance of 3.5 pF. Note that the bath T measured with a thermometer next to the sample didn't go below $\approx 120 \text{ mK}$ because of the power dissipated by the low- T amplifier.

range where $F \approx 1$ (see fig. 2).

III. LOCALIZATION RADIUS

We evaluate the localization radius in our samples with the help of magnetoresistance measurements in a perpendicular magnetic field B . A typical dependence $R_{\square}(B)$ is plotted in fig. 3. An exponential growth of the resistivity with B is observed at not too small fields, as expected for the VRH conduction. According to [6], for $B \leq (\hbar c / e a^2)(T/T_0)^{1/3}$ the magnetoresistance is described by the formula $\ln R(B)/R(0) = 1/360 e^2 a^4 (T_0/T) B^2 / c^2 \hbar^2$, where the numerical prefactor was derived assuming identical localization centers (impurities). In our case the localization occurs in a random disorder potential, so that a has a meaning of the average localization radius. The data in fig.3 corresponds to $a \approx 30 \text{ nm}$ (solid line). In weak magnetic fields a strong negative magnetoresistance is observed, similar to numerous previous reports.

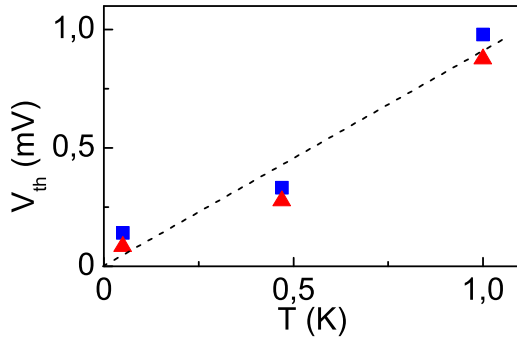


FIG. 2. Nonlinearity vs temperature. The T dependence of the threshold bias voltage where the I - V curves deviate from the linearity by 20%. The triangles and squares correspond, respectively, to $R_{\square} = 1.6 \text{ M}\Omega$ and $R_{\square} = 18 \text{ M}\Omega$ (at $T = 0.47 \text{ K}$).

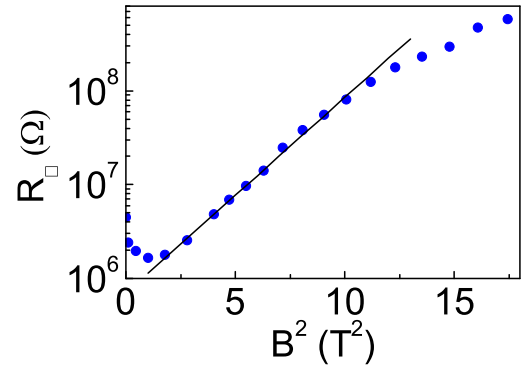


FIG. 3. Exponential magnetoresistance. A typical trace $\ln R$ vs B^2 (symbols) taken at $T = 0.47 \text{ K}$ and a fit according to the VRH predictions (line, see text)

The origin of this effect could be related to a suppression of the interference contribution to the amplitude of a hop [7] or a nonmonotonic change of the density of states [6, 8] in magnetic field. We don't discuss this effect in detail here.

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